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Transformer Oil Degradation on PV Plants – A Case Study

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Summary

The use of renewable energy sources for power generation is becoming more common and global warming effects along with an increase in power demand have resulted in more countries adopting renewable resources for power generation. Photovoltaic (PV) systems are part of the renewable resources being widely adopted by developing countries such as South Africa and as such, an investigation into the considerations and impact that these PV systems have on the electrical network and components connected to them is paramount in ensuring effective power generation.

This paper presents a case study of dissolved gas analyses (DGA) done on mineral oil-filled transformers connected to a PV power plant. The DGA studies were necessitated by the abnormal, peculiar gassing patterns exhibited by the transformers after being in-service for less than a year. The results for the DGA were obtained from manual oil samples tested in a materials and oil laboratory.

Possible causes of oil degradation in transformers connected to PV plants are also presented, which could assist customers and manufactures when designing transformers for PV power plant applications with being cognisant of the loading conditions and the selection of materials that will be in direct contact with the oil. Possible solutions to excessive gassing and quality degradation of oil such as oil degassing, regeneration and replacement have been investigated, presented and compared in terms of the efficacy of improving the longevity of the oil and the cost associated with the implementation thereof.

Keywords:

Dissolved gas analysis, Photovoltaic plants, Abnormal gassing, Transformers, Oil degradation.

1. Introduction

Sub-Saharan Africa, like the rest of the world, is facing an increase in energy demand with the permeation of urbanisation. The need for additional power to meet the growing demand, specifically clean energy in an effort to reduce emissions and minimize reliance on fossil fuels like coal, has led to South Africa establishing the Renewable Energy Independent Power Producers (REIPP) procurement programme for the installation of renewable energy technologies. As such; renewable energy sources such as Photovoltaic (PV) energy prove a great alternative to curb or at least balance the current energy crisis [1][2].

PV power systems transform solar energy into electrical energy through the use of solar radiation, and thus these systems use no fossil fuels[3]. PV power systems may be connected to a grid for distributed generation [1][3]. In such a case, an array of PV cells are connected in series to an inverter which converts the direct current (DC) power generated by the array to the alternating current (AC) power of the utility system [1][2] Step-up transformers, which are central to the distribution of the generated power, are then connected to the inverter in order to transform the generated low voltage power to the medium voltage power of the utility network connected to the PV plant [2].

In order to ensure efficient transformation and distribution of the generated power, the transformer connected to the PV plant has to be able to handle the fluctuating patterns of the generated power due to the erratic nature of solar energy. The fluctuation patterns of the solar plant may cause harmonics in the system, resulting in overheating of the transformer and a shortened lifetime [1]. Transformer components such as the conductors and the insulation thereof need to be afforded the ability to withstand these fluctuating patterns throughout the transformer lifetime. It is for this reason that the quality of the transformer oil, which offers cooling and dielectric properties to the components, should be able to continue providing this performance support to the transformer in order to ensure the efficient operation of the transformer [4].

The paper presents a case study done for a DGA performed on transformers in service which exhibited abnormal gassing patterns after only one year in operation. Section 2 elaborates on dissolved gas analysis and interpretation, Section 3 presents the case study which includes the collected DGA results along with the observed gassing patterns. Due to the observed results, Section 4 discusses possible causes of oil deterioration, conclusions are drawn in Section 5 based on the evidence presented and recommendations for PV transformers are then given in Section 6.

2. Dissolved Gas Analysis (DGA)

Oil-filled transformers in operation generate gases to some extent at normal operating temperatures which are manageable and which do not result in decomposition of the electrical components along with the insulating materials. High gas concentrations are a consequence of electrical disturbances and thermal decomposition of the insulating materials and the electrical components within the transformer. Transformer mineral insulating oils are made of hydrocarbon molecules which breakdown during electrical and thermal faults thus causing active hydrogen atoms and hydrocarbon fragments which may then combine with the hydrogen atoms to form gases, normally combustible, within the oil. Gases usually detectable and commonly used for such assessments include hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2) and Nitrogen (N_2). The formation of these gases is dependent upon the temperature of the activity and may decay cellulose insulating material present in the transformer and further contribute to more faults arising. Oil sample analyses are then performed to monitor the gas levels within the oil [4].

Dissolved Gas Analysis (DGA) is a method of oil sample analysis used to indirectly monitor the condition of the transformer by assessing the quantity and rate of increase of gases dissolved in the oil in high voltage equipment [5]. The levels and the concentration of the formed gases can be traced to particular faults or be an indication of stray gassing (gassing at relatively low temperatures, as a result of degradation under thermal stress, without an actual thermal fault) as is determined by some of the DGA interpretation tools described in Table 1, from references [5] to [8].

Table 1: DGA interpretation tools

DGA Methods	Purpose	Measured gases (ppm)
CIGRE	Analyses of key gas ratios and gas concentrations	Gas ratios: C_2H_2/C_2H_6, H_2/CH_4, C_2H_4/C_2H_6, C_2H_2/H_2 and CO/CO_2
Dornenburg Ratio	Identifies thermal faults, corona discharge and arcing	H_2, CH_4, C_2H_2, and C_2H_4
Duval Analysis	Partial discharges, electrical faults (high and low energy arcing), thermal faults (hot spots of various temperature ranges) and stray gassing	H_2, CH_4, C_2H_4 and C_2H_2
IEC Ratios	Used in detection of normal ageing, partial discharge of low and high energy densities, thermal faults and electrical faults of varying severity	Resembles the Rogers Ratio method but excludes the C_2H_6/CH_4 ratio.
Key Gas	Measures the gases released from insulating oil after a fault such as overheating of oil, overheating of cellulose, corona (partial discharge) and arcing	Concentrations of key gases (C_2H_4, CO, H_2, C_2H_2)
Nomo graph	Improves the accuracy of fault diagnosis by combining fault gas ratios and the concept of Key Gas threshold	concentrations of key gases (C_2H_4, CO, H_2, C_2H_2)
Rogers Ratio	Detecting conditions such as normal ageing, partial discharge with or without tracking, and electrical and thermal faults of varying severity	Gas ratios: CH_4/H_2, C_2H_6/CH_4, C_2H_4/C_2H_6 and C_2H_2/C_2H_4

Shown in Table 2 are the types of faults associated with gas concentration levels as adapted from IEC [7] and from [8].

Table 2: Some DGA Guidelines on key gas concentrations

Gases	90% Typical values (µl/l) [7]	Action Limits(>) [8]	Potential Fault Type [8]
H_2	60-150	100	Corona, Arcing
CH_4	40-110	80	Sparking
CO	540-900	1000	Severe Overheating
CO_2	5100-13000	15 000	Severe Overheating
C_2H_2	3-50	7000	Arcing
C_2H_4	60-280	150	Severe Overheating
C_2H_6	50-90	35	Local Overheating

If the key gas concentrations exceed those in Table 2 for example, techniques such as the Duval Analysis and the key gas ratios in Table 3 may be used to determine the root cause of the fault. Figure 1 shows the Duval Pentagon 1, part of the latest developments in the Duval analysis tools (the other being Pentagon 2).

Table 3: Guidelines on the interpretation of key gas ratios [8]

Ratio	**Interpretation**
CO_2/CO	1. Ratio >10 = Fault of temperature < 150℃ 2. Ratio < 3 = Fault in paper of temperature > 200℃
O_2/N_2	1. Decreasing ratio between samples indicates possible excessive heating 2. Ratio < 0.3 = Indicates excessive consumption of oxygen
C_2H_2/C_2H_4	1. Ratio < 0.1 = Type T2 (thermal fault between 500℃ and 700℃) 2. Ratio < 0.2 = Type T3 (thermal fault greater than 700℃) 3. 0.6 ≤ Ratio ≤ 2 = Type D2 fault (Arcing) 4. Ratio > 1 = Type D1 fault (Sparking)
C_2H_6/H_2	3. Ratio < 0.1, 0.1-1 = D1 4. 0.1 ≤ Ratio ≤ 1 = Type D2 fault 5. Ratio > 1 = Low to high temperature Thermal fault

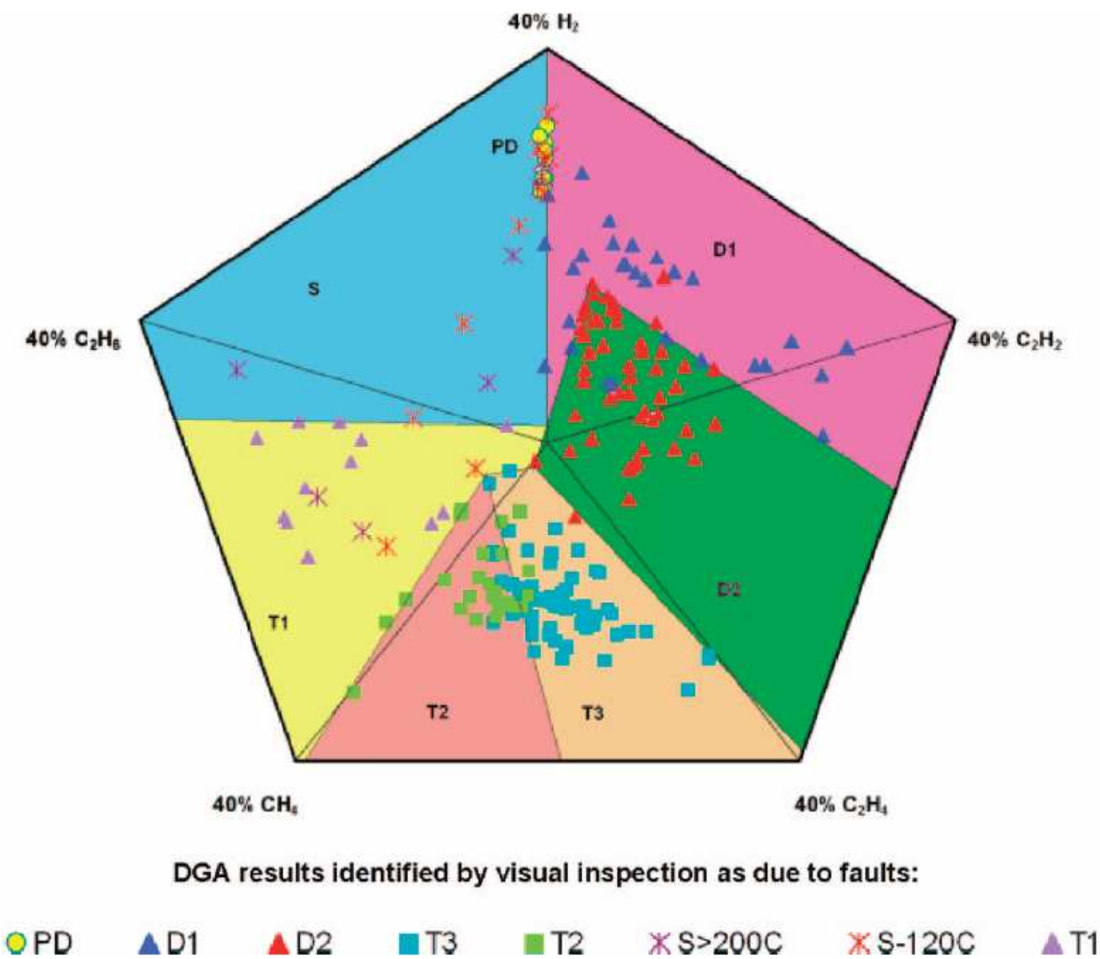

Figure 1: Duval Pentagon 1 [9]

The total combustibles gases (TCG) present within the transformer oil can also be compared against the normal limits to further diagnose the severity of the gassing behaviour as pertains to the safe operation of the transformer and its reliability. The transformer's operating conditions based on the TCG values are described in Table 4, adopted from IEEE [16].

Table 4: TCG Interpretation guidelines [16]

Legend	TCG (ppm)
Condition 1: TCG below this level indicates the transformer is operating satisfactorily. Any individual combustible gas exceeding specified levels should prompt additional investigation	720
Condition 2: TCG within this range indicates greater than normal combustible gas level. Any individual combustible gas exceeding specified levels should prompt additional investigation. Action should be taken to establish a trend. Fault(s) may be present	721-1920
Condition 3: TCG within this range indicates a high level of decomposition. Any individual combustible gas exceeding specified levels should prompt additional investigation. Immediate action should be taken to establish a trend. Fault(s) are probably present.	1921-4630
Condition 4: TCG exceeding this value indicates excessive decomposition. Continued operation could result in failure of the transformer. Proceed immediately and with caution	>4630

3. Methodology

3.1 Case Study

Several transformers at three different South African PV plants were observed to be exhibiting abnormal gassing patterns. Oil samples were collected from transformers and DGA was performed in order to identify the root cause of the observed patterns.

The PV plants are located at two different provinces, with different climatic conditions. Two of the PV plants are located in the Northern Cape Province [10] while the other is situated in the North West Province [11]. The two locations are more than a 1000km apart and with differing socio-economic landscapes, as such, the rate of energy generation with regards to the demand requirements of the area will differ. The direct normal irradiation is 2600-2900kWh/m^2 for the Northern Cape plants and 2150-2450 kWh/m^2 for the North West plant [12]. Thus it is not expected that the gassing behaviour due to operating conditions; be the same.

The units for all plants were manufactured by the same manufacturer, with the transformers manufactured for the Northern Cape plants being manufactured before those of the North West plant. The same design and materials were used for the Northern Cape units. The units for the North West plant were manufactured when the investigations were at an advanced stage, with the design modified and some materials suspected of being incompatible with the oil being replaced for these units.

The transformers studied and presented in this paper were all of the same MVA and kV ratings and during the design phase, they were treated as sister units.

3.2 Observed Gassing Patterns

Oil samples were taken from different units in each of the PV plants to perform the dissolved gas analysis and gassing trends were established, with analyses made using the tools and methodologies presented in Section 2. Table 5 shows the results of the absolute values of the DGA measurements for some of the units at each PV plant.

Table 5: DGA oil sample results (ppm)

Transformer Unit	H_2	O_2	N_2	CO	CO_2	CH_4	C_2H_4	C_2H_6	C_2H_2	TCG
North West PV plant (NW)										
Unit NW1	9671	5904	65918	84	978	1963	N/D	559	N/D	12277
Unit NW2	9345	6281	78245	166	2098	1488	8	276	N/D	11283
Unit NW3	10000	4462	61212	70	808	2481	5	637	N/D	14110
Northern Cape PV plant A (NCA)										
Unit NC1	1478	28899	72484	28	860	438	36	561	N/D	2541
Unit NC2	1562	26189	68661	33	965	417	13	619	N/D	2644
Unit NC3	1598	32311	78590	1	835	543	132	479	N/D	2753
Northern Cape PV plant B (NCB)										
Unit NCB1	1334	1901	77903	101	1839	270	74	578	N/D	2373
Unit NCB2	2203	1715	78185	128	1795	594	5	838	N/D	3768
Unit NCB3	1953	2410	73352	117	1870	467	N/D	785	N/D	3322

The oil samples in Table 5 were all collected from the transformers in October 2014 while the transformers were in service. The colour legend used in the TCG column corresponds to the transformer operating conditions as given in Table 4. From the guidelines given in Table *2* and Table 4 in Section 2, it can be seen that the sampled units for all the plants are well above normal operating values, with the units at the NW plant showing noticeably high values of hydrogen and TCG. The units at the NCA and NCB plants show similar gassing patterns with the absolute detected gas values being significantly lower than those of the NW plant. This observation may also have been influenced by the climatic and demand requirements of the regions at which these units operate. Table 6 shows the different gas ratios as given by the guidelines of Table 3.

Table 6: Calculated key gas ratios

Transformer Unit	CO_2/CO	O_2/N_2	C_2H_2/C_2H_4	C_2H_6/ H_2
Unit NW1	11.64	0.09	N/D	0.058
Unit NW2	12.64	0.08	0	0.030
Unit NW3	11.54	0.073	0	0.064
Unit NCA1	30.71	0.40	0	0.380
Unit NCA2	29.24	0.38	0	0.40
Unit NCA3	835	0.41	0	0.30
Unit NCB1	18.21	0.024	0.22	0.433
Unit NCB2	14.02	0.022	0	0.380
Unit NCB3	15.98	0.033	N/D	0.401

The calculated key gas ratios give an indication of different faults, be it incipient or active faults, within the units, such as a temperature fault at less than 150°C as well as low and high energy discharge. The observed faults are also interpreted using the Duval Analysis, which includes both the Duval Triangles (Tria.) 1, 4 and 5 and Duval Pentagons (Pent.) 1 and 2, with the results thereof given in .

Table *7*.

Table 7: Duval analysis for the DGA results

Transformer Units	Duval analysis				
	Tria. 1	**Tria. 4**	**Tria. 5**	**Pent. 1**	**Pent. 2**
Unit NW1	PD	S	S	S	S
Unit NW 2	PD	S	S	S	S
Unit NW 3	PD	S	S	S	S
Unit NCA1	T1	S	O	S	S
Unit NCA2	T1	S	O	S	S
Unit NCA3	T1	S	Non-determinable	S	S
Unit NCB1	T2	S	O	S	S
Unit NCB2	PD	S	O	S	S
Unit NCB3	PD	S	S	S	S

Due to the excessive nature and the production rates of hydrogen, the transformer oil was replaced in all the affected units and a new DGA trend was established for the units to ascertain whether there was an appreciable, observable difference in the results. Table 6 gives the results collected for all the units with the new oil. The new oil samples were collected and tested between 24 November and 14 December 2015.

Table 8: DGA oil sample results after oil replacement (ppm)

Transformer Units	H_2	O_2	N_2	CO	CO_2	CH_4	C_2H_4	C_2H_6	C_2H_2	TCG
NW										
Unit NW1	472	19807	73610	90	2569	160	3	312	0	1037
Unit NW2	1445	41742	94188	42	1373	360	0	353	0	2200
Unit NW3	460	26891	76630	70	2118	186	3	322	0	1041
NCA										
Unit NCA1	150	19455	90800	89	2291	84	0	222	0	545
Unit NCA2	474	22808	81303	95	2053	93	0	204	0	866
Unit NCA3	294	36284	78810	37	1287	73	0	213	0	617
NCB										
Unit NCB1	369	7481	94422	243	6191	171	10	673	0	1466
Unit NCB2	657	4855	76973	249	4246	312	8	798	0	2024
Unit NCB3	455	6447	79188	241	4429	199	8	457	0	1360

As can be seen from the results in Table 8 the replacement of the transformer oil had a great impact on the gassing patterns which points to oil degradation in the first samples collected. The units were monitored continuously after the oil replacement and it was observed that gas levels continued to increase in some units and remained within typical values in other units. Due to the observation of the new gassing patterns, Section 4 discussed other causes of oil degradation for transformers in-service and oil quality test results of some of the transformers in question.

4. Oil Deterioration Factors

Other causes of abnormal gassing behaviour in mineral oil-filled transformers are the presence of contaminants as a result of poorly monitored oil processing and filling processes as well as a result of chemical reactions between the oil and other transformer materials it is in contact with. The presence of contaminants is monitored by assessing the quality of the oil. Five key mineral oil quality parameters are normally monitored, viz; dielectric strength, moisture content, interfacial tension, acidity and the dielectric dissipation factor (tan delta). The colour of the oil sample serves as a visual indicator of the presence or absence of floating debris. These parameters are used to assess whether there are contaminants in the oil or not. Depending on which of the five parameters is deteriorating, the contamination can be classified as either soluble polar or non-polar contaminants. Polar contaminants and products of oxidation tend to make the normally non-polar mineral oil hydrophilic, causing its dielectric strength, acid content and interfacial tension to deteriorate. An increase in hydrophilic contaminants deteriorates the interfacial tension rapidly. In an oil-filled transformer, mineral oil subjected to a rapid rise in temperature followed by a rapid drop in temperature leads to the formation of condensation that ultimately increases the moisture content and sludge formation and a further decrease in the oils dielectric strength. The presence of sludge leads to reduced cooling capacity and further rises in the transformers operating temperatures.

Materials whose reactions with oil are known to lead to the formation of contaminants include galvanized steel, certain zinc oxide paints used to coat the inside of the transformer tank, glues and varnishes used on the surfaces of core laminations as well as the breakdown of oil when in contact with overheated core lamination edges and due to reactions with bare copper surfaces.

During the monitoring of the transformers at the PV stations in the two provinces, oil quality tests were performed alongside the DGA tests.

During the initial assessment period, the oil quality parameters of the energised units had significantly deteriorated. Because the internal inspections revealed, primarily, evidence of the overheating of metallic parts, it was initially suspected that in addition to overheating due to the increase in Eddy losses as a result of the higher levels of the actual THD from the inverters (as opposed to the theoretical value), material incompatibility had also contributed to the observed gassing behaviour.

After the units were modified and the oil was replaced, the oil quality parameters were once again monitored. During the second monitoring period, a similar degradation in the oil quality parameters was observed. Table 9 to Table 13 shows the change in the oil quality parameters of three random units from the NCB PV station, with a period of 1 month between the previous and current samples.

Table 9: Dielectric strength of the evaluated transformer oil samples

Transformer Unit	**Measured value (kV)**		**Limit – IEC 60156 (kV)**
	Previous sample	**Current sample**	
Unit NCB1	59	31	≥30
Unit NCB2	87	74	≥30
Unit NCB3	74	83	≥30

Table 10: Water/ moisture content of the evaluated transformer oil samples

Transformer Unit	**Measured value (ppm)**		**Limit – IEC 60814 (ppm)**
	Previous sample	**Current sample**	
Unit NCB1	27	27	≤40
Unit NCB2	11	10	≤40
Unit NCB3	10	20	≤40

Table 11: Interfacial tension of the evaluated transformer oil samples

Transformer Unit	**Measured value (mN/m)**		**Limit – ISO 6295 (mN/m)**
	Previous sample	**Current sample**	
Unit NCB1	14	14	≥20
Unit NCB2	26	25	≥20
Unit NCB3	15	14	≥20

Table 12: Dielectric dissipation factor (tan delta) of the evaluated transformer oil samples

Transformer Unit	**Measured value (at 90℃)**		**Limit – IEC 60247 (at 90℃)**
	Previous sample	**Current sample**	
Unit NCB1	0.22370	0.1888	≤0.50
Unit NCB2	0.00842	0.01333	≤0.50
Unit NCB3	0.18410	0.1262	≤0.50

Table 13: Acidity of the evaluated transformer oil samples

Transformer Unit	**Measured value (mg KOH/g)**	**Limit – IEC 62021-1 (mg KOH/g)**
Unit NCB1	0.19	≤0.30
Unit NCB2	0.01	≤0.30
Unit NCB3	0.12	≤0.30

Another observation made was that the excessive gassing and oil deterioration patterns were cyclic, especially the changes in the dielectric strength and moisture content; with a drop in the dielectric strength and an increase in moisture content witnessed over the summer months (December to February period – higher solar radiation months).

Materials suspected of being responsible due to either being recently introduced in the manufacturing process or as a result of a change in the supplier; were thus tested for compatibility with the mineral oil. The compatibility test results proved inconclusive, and the use of the suspected materials was discontinued for units manufactured subsequently. These units were primarily those designated for the NW PV plant.

Similarly, the oil in these units exhibited abnormal but steady gassing behaviour and deteriorating moisture content and dielectric strength over the summer months.

5. Conclusions

The oil analysis discussed in this document shows evidence that potentially indicates oil degradation as a result of thermal stress, due to hotspots in metallic parts. The cyclic nature of the abnormal gassing behaviour and oil quality deterioration is mainly observed during the higher solar radiation months. Initially, material compatibility issues were suspected to be responsible for the gassing behaviour and deterioration in oil quality and material compatibility tests were thus conducted. The compatibility tests were however inconclusive, and the role of incompatible material in the rapid deterioration of the oil was further contradicted when similar behaviour was observed on units that were manufactured with compatible materials. Oil degradation plays a part in the gassing activity within a transformer, as evidenced by the witnessed effects that replacing the oil had on the transformer.

6. Recommendations

In a PV plant the inverter converts DC to AC power, which results in harmonic currents being generated. These harmonic currents could have a significant effect on the losses harmonic currents could cause an increase in transformer losses, due to the variation in the frequency linked with the skin effect of the conductive materials in the transformer and consequently lead to the rise in oil temperature; leading to gas formation and an accelerated degradation of the oil and insulation.

It is therefore important that both the manufacturer and the client conduct thorough harmonic studies to correctly determine the total harmonic distortion and the order of the harmonics introduced into the transformer; thereby allowing for more adequate design philosophies to be adopted, for example, the use of forced and/or directed cooling schemes to reduce localised overheating.

Lastly, more moisture tolerant transformer oils and cellulose insulation materials of a higher thermal class, such as ester oils should be considered, in order to accommodate the wide temperature gradients seen by transformers in such applications.

Doing the above mentioned could increase the lifespan of the transformer, its oil and insulation, and also increase the availability of a PV plant.

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